

A Discovery of a Peculiar Pulsar in the Small Magellanic Cloud

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(Received ; accepted)

Abstract

We report on a peculiar X-ray binary pulsar IKT 1 = RX J0047.3–7312 observed with XMM-Newton in Oct. 2000. The X-ray spectrum is described by a two-component spectrum. The hard component has a broken power-law with respective photon indices of 0.2 and 1.8, below and above the break energy at 5.8 keV. The soft component can be modeled by a blackbody of $kT = 0.6$ keV. The X-ray flux shows a gradual decrease and periodic variations of about 4000 s. The averaged flux in 0.7–10.0 keV is 2.9×10^{-12} ergs cm $^{-2}$ s $^{-1}$, which is ~ 10 times brighter than that in a ROSAT observation in Nov. 1999. In addition to the 4000-s variation, we found coherent pulsations of 263 ± 1 s. These discoveries strengthen the Be/X-ray binary scenario proposed by the ROSAT and ASCA observations on this source, and confirm that most of the hard sources in the Small Magellanic Cloud are X-ray binary pulsars. A peculiar property of this XBP is that the coherent pulsations are found only in the soft component, and the folded light curve shows a flat top shape with a sharp dip. We discuss the nature of this XBP focusing on the peculiar soft component.

Key words: Pulsars: individual (IKT 1) — Stars: neutron — X-rays: spectra — X-rays: transient

1. Introduction

More than 30 X-ray binary pulsars (XBP) have been discovered in the Small Magellanic Cloud (SMC) by the recent satellites such as ASCA, RXTE, Chandra, and XMM-Newton (e.g., Yokogawa et al. 2003). Most of the XBPs in the SMC have been classified, or proposed to be Be/X-ray binaries with the estimated ages of $\sim 10^7$ yrs. The number of the XBPs normalized to the galaxy mass is far larger in the SMC than in our Galaxy (Haberl & Sasaki 2000; Yokogawa et al. 2003). This high population of XBPs would be good evidence for the active star formation in the SMC of $\sim 10^7$ yrs ago.

Other than the population study of the X-ray sources, the SMC is a good local galaxy for the study of individual X-ray sources such as the emission mechanism of XBPs, because the interstellar extinction for the member sources is very low and the line-of-sight galaxy depth is small (~ 10 kpc) compared to the SMC distance of ~ 60 kpc (Harries, Hilditch, & Howarth (2003) and references therein). The former gives us soft X-ray information down to a few-hundred eV, while the latter provides us with a more accurate distance, and hence the X-ray luminosity, than those of the galactic sources. The large collective area of XMM-Newton enables us to perform the X-ray spectroscopy down to the luminosities of $\sim 10^{34}$ ergs s $^{-1}$ (e.g., Sasaki, Pietsch, & Haberl 2003) even for more distant (60 kpc) XBPs than those in our Galaxy (typically 1–20 kpc).

IKT 1 was first discovered by Inoue, Koyama & Tanaka (1983) with Einstein. ROSAT observed this source many times and Haberl & Sasaki (2000) proposed this source to be a Be/X-ray binary candidate from the flux variability and the existence of an optical counterpart with emission lines. ASCA also detected this source and found a flare-like behavior (Yokogawa et al. 2003). Yokogawa et al. (2003) plotted hardness ratios of X-ray sources in the SMC against their lu-

minosities and found that XBPs reside in a restricted region. Since IKT 1 is located in this region, IKT 1 is likely to be an XBP.

Using the XMM-Newton archive data, we found coherent X-ray pulsations from this source. This paper reports on the discovery of a 263-s pulsation and the timing and spectrum analysis. Discussion on the nature of IKT 1 is made focusing on the phase-resolved spectroscopy. Independent detection of the 263-s pulsation was recently reported by Haberl & Pietsch¹. The source distance is assumed to be 60 kpc, the same value as the SMC (Harries, Hilditch, & Howarth 2003).

2. Observation

The main objective of the XMM-Newton (Aschenbach et al. 2000) observation made on Oct. 15, 2000 was to study a supernova remnant (SNR), IKT 5 (Inoue, Koyama & Tanaka 1983), and other X-ray sources around this SNR. In this field, we found IKT 1 with a higher X-ray flux than the previous observations of ROSAT and ASCA, and hence we study the X-ray properties of this source. Since EPIC/PN (Strüder et al. 2001) has better time resolution and statistics than MOS1/2 (Turner et al. 2001), and IKT 1 accidentally fell in the CCD dip of MOS2, we concentrate on the X-ray data from EPIC/PN, and use the MOS1 and 2 data for the consistency check.

PN was operated in the extended full frame mode with the medium filter and the time resolution of 200 ms. We used the version 5.4.1 of the Standard Analysis System (SAS) software for the event selection. From the detected PN events, we selected those with the PATTERN keywords between 0 and 4 as X-ray events. The exposure time was ~ 22 ks.

¹ Haberl & Pietsch appeared in astro-ph (0311092, accepted to A&A) after we submitted the present paper.

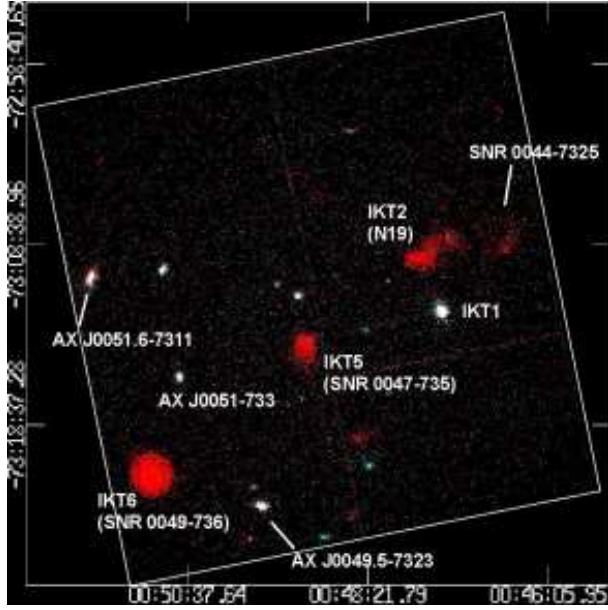


Fig. 1. XMM-Newton/PN image around IKT 5. The soft (0.5–2.0 keV) and hard (2.0–7.0 keV) band images are represented with red and blue colors, respectively. The images have been smoothed to a resolution of 5''. XRBPs and SNRs in the FOV are designated with their names. The FOV of the PN detector is shown with the solid square.

3. Results

3.1. Image Analysis

The hard (2.0–7.0 keV) and soft (0.5–2.0 keV) band X-ray images are shown with two colors in Figure 1. Three XRBPs (AX J0049.5–7323, AX J0051–733, AX J0051.6–7311; Yokogawa et al. 2000cc, Imanishi et al. 1999, Yokogawa et al. 2000bb) and 4 SNRs (0044–7325, IKT 2 = N19, IKT 5 = 0047–735, IKT 6 = 0049–736; e.g., Wang & Wu 1992) are clearly found in the field of view (FOV). All the XRBPs appear as white point sources, and the SNRs show red extended structures. Blue color sources may be extra galactic AGNs. All the three pulsars mentioned above are identified with emission line objects (ELOs) catalogued by Meyssonnier & Azzopardi (1993) (Haberl & Sasaki 2000). The coordinates of these pulsars derived from the PN data are systematically shifted from the positions of the optical counterparts by $(\Delta\text{R.A.}, \Delta\text{Dec.}) = (-2.^{\circ}4, -0.^{\circ}1)$. We hence fine-tuned the PN coordinates to the optical coordinates. After this tuning, the root-mean-square of the differences between the PN and the optical positions for the three pulsars is $(\Delta\text{R.A.}, \Delta\text{Dec.}) = (0.^{\circ}2, 0.^{\circ}7)$. This can be used as a typical positional error between the two frames.

The brightest source in the FOV is the white point source at the south of IKT 2. The fine-tuned position is R.A. = $00^{\text{h}}47^{\text{d}}23^{\text{s}}.3$, Dec. = $-73^{\circ}12'27''$ (J2000), and hence we designate this source as XMMU J004723.3–731227. Although 1σ -statistical error of this source position is only $0.^{\circ}1$, a realistic error would be $\sim 0.^{\circ}7$ (see the previous paragraph). Since all the error regions of XMMU J004723.3–731227, IKT 1 (Inoue, Koyama & Tanaka 1983), and RX J0047.3–7312 (Haberl & Sasaki 2000) overlap, we conclude these three sources are the same X-ray object.

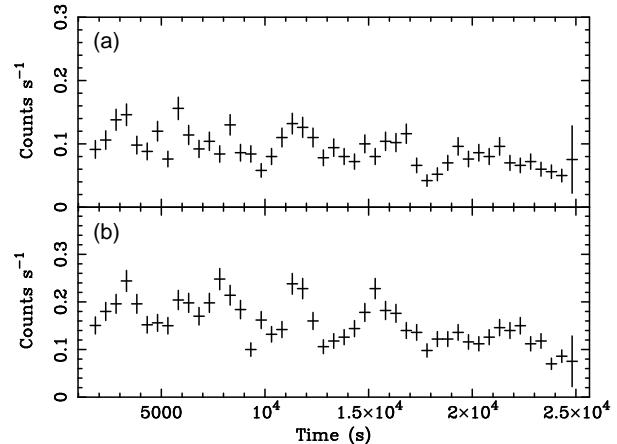


Fig. 2. Light curves of IKT 1 in the 0.5–2.0 (a), and 2.0–10.0 keV (b) bands.

3.2. Timing Analysis

For the timing analysis of IKT 1, X-ray photons were extracted from a circular region of $40''$ radius centered on IKT 1 in the PN image. The light curves with the time bin of 500 s in the energy bands of 0.5–2.0 and 2.0–10.0 keV are shown in Figure 2. In both the energy bands, we see several flare-like events on the general trend of decreasing flux.

After the barycentric arrival time corrections, we searched for periodicity in the energy bands of 0.5–2.0 and 2.0–10.0 keV, using a Fast Fourier Transformation algorithm. Figure 3 shows the resultant power density spectra in the 3.8×10^{-5} – 2.5 Hz frequency band. In the 0.5–2.0 keV band, a maximum power of 81.6 was obtained at the frequency of 3.82×10^{-3} Hz ($= 262$ s). Since the probability to detect such a large power in any frequency from random events is only $\sim 1 \times 10^{-13}$, the detection of the coherent pulsations is highly significant. In the 2.0–10 keV band, however, we see no significant power excess at this frequency. The other large power peak at 2.29×10^{-4} Hz is due to the periodic flares. Unlike the coherent pulsations, this peak is found in both the energy bands.

We next performed epoch folding searches for the periods near the two power-peak frequencies. The flare-like events are found to have the most probable period of 3920 ± 150 s. The barycentric period of the coherent pulsations is determined to be $P = 263 \pm 1$ s. Figure 4 shows the folded pulse profiles at the period of 263 s in the 0.5–2.0 and 2.0–10.0 keV bands. We see no pulse modulation in the hard X-ray band, while the pulse profile found in the soft band is very peculiar: a flat top profile with a V-shape dip.

3.3. Spectral Analysis

The X-ray spectrum was extracted from the same region as the timing analysis (the $40''$ -radius circle), while the background spectrum was extracted from the annular region around the source with the inner and outer radii of $40''$ and $80''$, respectively.

Since the pulse profiles are energy dependent, we made X-

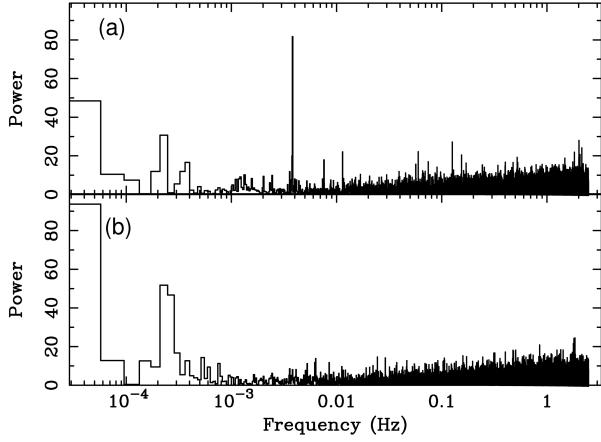


Fig. 3. Power spectra of IKT 1 in the 0.5–2.0 (a) and 2.0–10.0 keV (b) bands. The power is normalized to be 2 for random fluctuations. The peak at $\sim 3.82 \times 10^{-3}$ Hz is seen only in the 0.5–2.0 keV band.

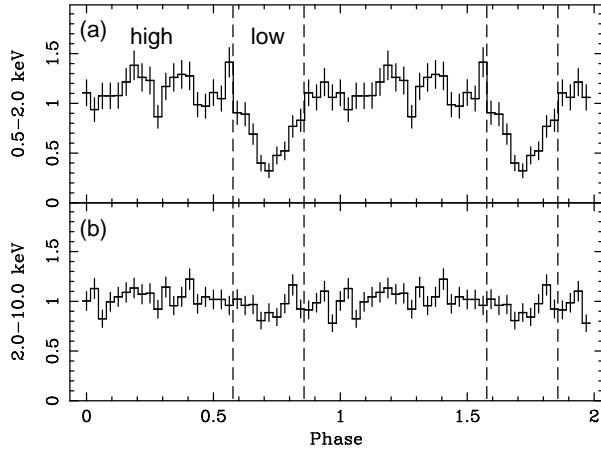


Fig. 4. Pulse profiles folded with the period of 263 s in the two energy bands: 0.5–2.0 keV (a), and 2.0–10.0 keV (b). The phase averaged count rates are normalized to be unity.

ray spectra separately, during the pulse minimum (low) and maximum (high) phases as shown in Figure 4. The background subtracted spectra for the low and high phases are given in Figure 5. In the hard X-ray band above ~ 3 keV, the two X-ray spectra show essentially the same profile and flux, while below ~ 2 keV the spectrum of the high phase shows a large excess over that of the low phase. This is in excellent agreement with that the X-ray pulsation is found only in the soft X-ray band.

Since both the spectra have a break at ~ 6 keV, we fitted the spectra with a broken power-law model. The photon indices, break energies and normalizations were simultaneously fitted, while the absorption columns were treated independently for each spectrum. In this paper, the photoelectric absorption was calculated using the cross sections by Morrison & McCammon (1983) assuming the solar abundance ratio (Anders & Grevesse 1989). This model reproduced the hard energy band well, but left large residuals at the soft energy band, and was statistically rejected with a $\chi^2/\text{d.o.f.}$ of

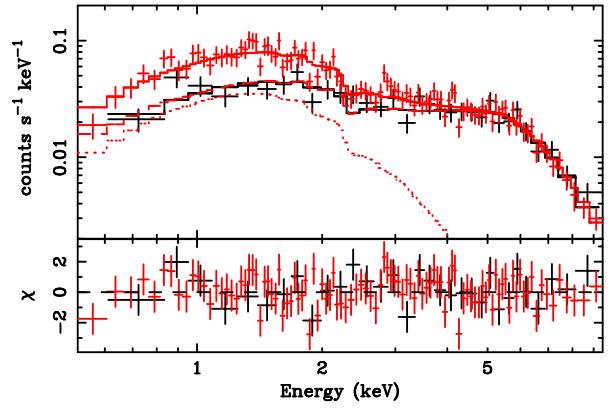


Fig. 5. (Upper panel:) Background-subtracted spectra in the “low” (black) and “high” (red) phases. The best-fit models and the blackbody component is shown with the solid and dot lines, respectively. (Bottom panel:) Residuals of the source counts from the best-fit models.

Table 1. Best-fit parameters with blackbody a bro-model.

Parameters	Value
Broken power-law	
Γ_1^*	$0.19^{+0.09}_{-0.30}$
Γ_2^*	$1.8^{+0.6}_{-0.4}$
Break Energy ..	$5.5^{+0.4}_{-0.6}$
Norm [†]	$6.7^{+1.0}_{-2.0}$
Blackbody	
kT (keV)	$0.59^{+0.11}_{-0.10}$
L_{total} (“low”) [‡] ..	< 0.5
L_{total} (“high”) [‡] ..	$1.4^{+0.6}_{-0.3}$
N_H [cm ⁻²]	$(9.6^{+4.6}_{-4.4}) \times 10^{20}$

Notes. Error regions correspond to 90% confidence levels.

*Photon indices below (Γ_1) and above (Γ_2) the break energy.

[†]Normalization at 1 keV ($\times 10^{-5}$ photons keV⁻¹ cm⁻² s⁻¹).

[‡]Total luminosity ($\times 10^{35}$ ergs s⁻¹) of the blackbody component in the “low” and “high” phases at the SMC distance (60 kpc; Harries, Hilditch, & Howarth 2003).

freedom (d.o.f.) = 160.9/129. Therefore the X-ray pulsation is not due to a periodic variation of the absorption.

We then added a blackbody (BB) as the soft component to the broken power-law model and performed a simultaneous fit for the low- and high-phase spectra. The normalizations of the BB component were treated as independent parameters between the two phases. As a result, the fit was acceptable with a $\chi^2/\text{d.o.f.} = 125.9/127$, with the best-fit parameters and models shown in Table 1 and Figure 5, respectively.

As for the 4000-s periodicity, we also made separate spectra for the high and low flux phases using the 4000-s folded light curve. These spectra are simultaneously fitted with the same two-component model as that for the case of the coherent pulsation (263 s); we fixed the spectral parameters to the best-fit values given in Table 1 except for the normalizations. In this

Table 2. Flux history of IKT 1

Satellite/Detector	MJD	Count rate*	Flux†
Einstein/IPC	44189	3.9 ± 0.8	5.2 ± 1.1
ROSAT/PSPC	48538	0 ± 3	0 ± 5
/PSPC	48728	11.0 ± 0.8	17 ± 1
/HRI	49098	1.3 ± 0.6	5 ± 2
/PSPC	49297	2.0 ± 0.6	2.9 ± 0.8
/HRI	49460	0.9 ± 1.0	4 ± 4
/HRI	49462	1.2 ± 1.4	5 ± 6
/HRI	49639	-0.4 ± 1.3	-2 ± 5
ASCA/GIS‡	50765	6.7
/GIS‡	51646	14
XMM/PN	51832	234 ± 3	29

Notes. Uncertainties correspond to $1-\sigma$ confidence regions.

*Count rate ($\times 10^{-3}$ cnts s^{-1}).

†X-ray flux ($\times 10^{-13}$ ergs $cm^{-2} s^{-1}$) in the 0.7–10.0 keV band. ‡Cited from Yokogawa et al. (2003).

case, we found an acceptable fit when the BB component is constant but only the normalizations of the broken power-law component varied between the high and low phases. Therefore the 4000-s variation is attributable to the broken power-law component.

4. Long-term Flux History

To investigate a long-term flux variability, we accessed the HEASARC archive and found that IKT 1 was in the field of 1 Einstein/IPC, 6 ROSAT/PSPC, and 4 ROSAT/HRI observations. We extracted the source events from the circular regions of $60''$, $50''$ and $20''$ radii centered on IKT 1 for the Einstein/IPC, ROSAT/PSPC and HRI observations, respectively. The backgrounds are estimated using the same size regions in blank skies near the source. After the background subtraction and the vignetting correction, we estimated the source fluxes using the PIMMS software, and using the ASCA best-fit model (Yokogawa et al. 2003). For comparison, the phase-averaged flux of the XMM-Newton observation was also estimated using the same ASCA model. In Table 2, we summarize the long-term X-ray fluxes (0.7–10.0 keV). We see that the XMM-Newton flux at MJD 51832 is higher than the Einstein, ROSAT and ASCA fluxes by more than ~ 5 times. Thus a large long-term flux variation is clearly found. It should be noted that, in the ASCA observation, IKT 1 exhibited a large flare of about 10^4 s duration (Yokogawa et al. 2003).

5. Discussion

5.1. X-ray population

The large long-term variability and the relatively low luminosity ($\sim 10^{35-36}$ ergs s^{-1} from the ROSAT to XMM-Newton observations) suggest that IKT 1 is a wind-fed binary system. Meyssonnier & Azzopardi (1993) detected an emission line star from a star cluster near IKT 1. Using the ROSAT observation, Haberl & Sasaki (2000) proposed that one of the stars in this cluster is an optical counterpart of IKT 1. We found only

one cluster member, OGLE 004723.37-731226.9², is within the refined position error of IKT 1 by EPIC/PN observation (the radius of $\sim 0.''7$), and hence this star must be an optical counterpart of IKT 1. The long-term X-ray variation, the pulsation of 263 s and the power-law spectrum strongly support that IKT 1 is a Be/X-ray binary pulsar (Be/XBP).

Since the space density of XBPs is extremely high in the south-west part of the SMC (see Figure 1), and most of the XBPs are Be/XBPs or strong candidates (Imanishi et al. 1999, Yokogawa et al. 2000bb, Yokogawa et al. 2000cc), this region must be an active star-formation site of some $\sim 10^7$ yrs ago. A H_I supergiant shell runs over this area (Stanimirović et al. 1999) and the age of the shell is estimated to be about 10^7 yrs. This supergiant shell, therefore, probably triggered the proposed star formation activity about 10^7 yrs ago.

5.2. Origin of the Soft Component

Although our results put IKT 1 to a strong candidate of Be/XBPs, the detailed X-ray features, the presence of the pulsating soft component and the absence of a pulsation in the power-law component, are rather peculiar compared to the other Be/XBPs. The pulse profile of a flat top with a V-shape dip is also unique.

Among the about 30 XBPs (and candidates) in the Magellanic Clouds, the soft component has been observed from only a few sources: SMC X-1 (Marshall, Becker, & White 1983; Woo et al. 1995), LMC X-4 (Woo et al. 1996), RX J0059.2-7138 (Kohno, Yokogawa, & Koyama 2000), EXO 05319-6609.2 (Haberl, Dennerl, & Pietsch 2003), and XTE J0111.2-7317 (Yokogawa et al. 2000aa) (see also Paul et al. 2002, and references therein), where the latter 3 are Be/XBPs. Thus IKT 1 may be the forth Be/XBP with a clear soft component.

For RX J0059.2-7138, the soft component is modeled as a thin thermal plasma of $kT = 0.37$ keV and exhibits no pulsation (Kohno, Yokogawa, & Koyama 2000). Thus the origin would be a largely extended plasma of a comparable size with the binary separation. EXO 053109-6609.2, on the other hand, shows a pulsation above 0.4 keV and both the soft and hard components may be pulsed (Haberl, Dennerl, & Pietsch 2003). Thus the origin of the soft component must be comparable with or smaller than the size of a neutron star (NS). XTE J0111.2-7317 has a peculiar spectrum of an inversely broken power-law model and shows pulsations both below and above the break energy (Yokogawa et al. 2000aa). Unlike these 3 sources, IKT 1 shows the X-ray pulsations only in the soft component.

Sasaki, Pietsch, & Haberl (2003) reported that two XBPs in the SMC show pulsations mainly in the soft band. AX J0049.5-7323 (Yokogawa et al. 2000cc) and RX J0101.3-7211 (Sasaki, Haberl, Keller, & Pietsch 2001) also show pulsations mainly in the soft components. The statistics of all the sources, however, were limited to distinguish whether or not the X-ray spectra are composed of pulsed soft and non-pulsed hard components. Accordingly, IKT 1 is the first object which exhibits a two-component spectrum with a pulsed soft component and a non-pulsed hard component.

² The data available at <http://bulge.astro.princeton.edu/~ogle/>

The soft component can be modeled with a BB radiation of 0.47 keV temperature. Using the X-ray luminosity of this BB in the high phase of the pulsation, the emission size is estimated to be $1.2 \times 10^2 \text{ km}^2$. This size is about 10% of the full surface of a NS, and hence the flux modulation along the NS rotation would be expected. A possible origin of the soft X-rays might be an opaque shell at the magnetosphere, which was first proposed by McCray & Lamb (1976) for the pulsating soft emission from Her X-1. Although the luminosity, hence the emission size of the soft emission from IKT 1 are significantly smaller than Her X-1, this model is another possible origin of the pulsating soft X-ray emission.

5.3. Origin of the Hard Component

In general, XBs exhibit a broken power-law spectrum in the hard component, which is likely coming from the small region near the pole, possibly the accretion column. The abnormal Thomson scattering in the strong magnetic field and the cyclotron resonance absorption/emission would be responsible for the spectral break. Since the hard component of IKT 1 has a typical broken power-law spectrum, it is highly possible that these X-rays originate from the accretion column near at the magnetic pole. A big puzzle, however, is that no coherent pulsation is found from this power-law component.

Except pulsations, the power-law component is highly variable with many flares with about 4000-s quasi-periodicity. A plausible case is that the 4000-s variation is due to quasi-periodic mass accretion. In fact, a long exposure (177 ks) observation of ASCA (Yokogawa et al. 2003) showed a large flare with the duration of about 10^4 s. No hint of the 4000-s variations was, however, found in the flare. The fainter flux of IKT 1 and the smaller effective area of ASCA than that of XMM-Newton might have made it impossible to detect the 4000-s variations if any.

Quasi-periodic oscillations (QPOs) at frequencies of 5–220 mHz have been observed from ~10 XBs to date (e.g., Boroson et al. 2000, and references therein). The canonical model of QPOs in XBs is either a model of the beat-frequency between those of rotations of the NS (ν_{ns}) and the Kepler motion of the inner disk (ν_K) (a beat frequency model: BFM), or a Keplerian frequency model (KFM). In the BFM, the QPO frequency (ν_{QPO}) equals $(\nu_K - \nu_{\text{ns}})$, where in the IKT 1 case $\nu_{\text{QPO}} = 0.23 \text{ mHz}$ and $\nu_{\text{ns}} = 3.82 \text{ mHz}$. As a result, ν_K of IKT 1 must be about 4 mHz and the corresponding Keplerian radius is about $7 \times 10^9 \text{ cm}$. The disk matter at the inner Keplerian radius should be in pressure balance to the magnetospheric field. Then assuming the radius and mass of NS to be $R_0 = 15 \text{ km}$, $m_x = 1.4M_\odot$, and using the X-ray luminosity of $L_x = 1.3 \times 10^{36} \text{ ergs s}^{-1}$, we estimate the surface magnetic field strength of the NS to be $\sim 4 \times 10^{13} \text{ G}$ (cf. Davidson & Ostriker 1973). This value is beyond the range of normal NSs (or XBs), and hence the BFM is unlikely. In the KFM, the Keplerian orbital period (frequency) of the inner disc is $\nu_K = \nu_{\text{QPO}} = 0.2 \text{ mHz}$, and hence the radius is about $5 \times 10^{10} \text{ cm}$, which is too far from the NS to produce the hard X-ray we observed.

In summary, IKT 1 exhibits many unusual properties as an XB, which must be a key for understanding the nature and X-ray emission mechanisms of this source. For a more quanti-

tative study of this peculiar pulsar, a very long exposure observation with high sensitivity instruments like XMM-Newton is highly anticipated.

The Einstein and ROSAT data are obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center. M.U. and S.T. are supported by JSPS Research Fellowship for Young Scientists. This work is supported by a Grant-in-Aid for the 21 century COE, "Center for Diversity and Universality in Physics".

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